THE MULTIPLE SCREEN DISC OXYGENATOR

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IN THE disc oxygenator, the blood to be oxygenated is exposed to an oxygen-containing atmosphere as a thin film upon one or more discs which revolve on a horizontal shaft. In the Bjork[1] pattern, formation of the film is accomplished by immersion of the bottom portion of each revolving disc in a river of blood, a technique which has proved effective for smooth-surfaced discs. In the pattern of the author's group, a screen disc has been utilized to provide more efficient oxygenation through better mixing of blood in the film.[3,4,6] Immersion of such a disc is productive of foaming; we have therefore produced our film in a different manner, namely by laying blood by means of a low-speed jet on the central solid portion of the screen disc.

Utilization of a screen to provide mixing in the film was the suggestion of Stokes and Flick[7] in Gibbon's laboratory. The pattern was modified by Miller, Gibbon and Gibbon,[5] who now utilize a stationary set of screens. Such a pattern as this poses a problem in creation of a smooth film at the start of each use of the oxygenator, and necessitates that the flow be constantly maintained to prevent break-down of the film into a series of rivulets. It is for this reason that we chose first to evaluate, and then to use regularly, a revolving disc of screen. We have been pleased with the spontaneous filming of the screen disc we use and with the uniform maintenance of the film whether the flow is stopped periodically or not.

THE BJORK PATTERN

The smooth-disc type of oxygenator was first used by Bjork and Crafoord for perfusion of the brain during temporary occlusion of the vena cavae for cardiac surgery. This oxygenator has subsequently been used with slight modification by Cross and Kay[2] for total cardio-pulmonary by-pass and intracardiac surgery. The Bjork oxygenator consists of a series of forty stainless steel rhodium-plated discs, each 0.5 mm. thick, 13 cm. in diameter, and mounted in groups of four on a rotating horizontal steel shaft. The discs are spaced on the shaft with 4 mm. between discs and 8

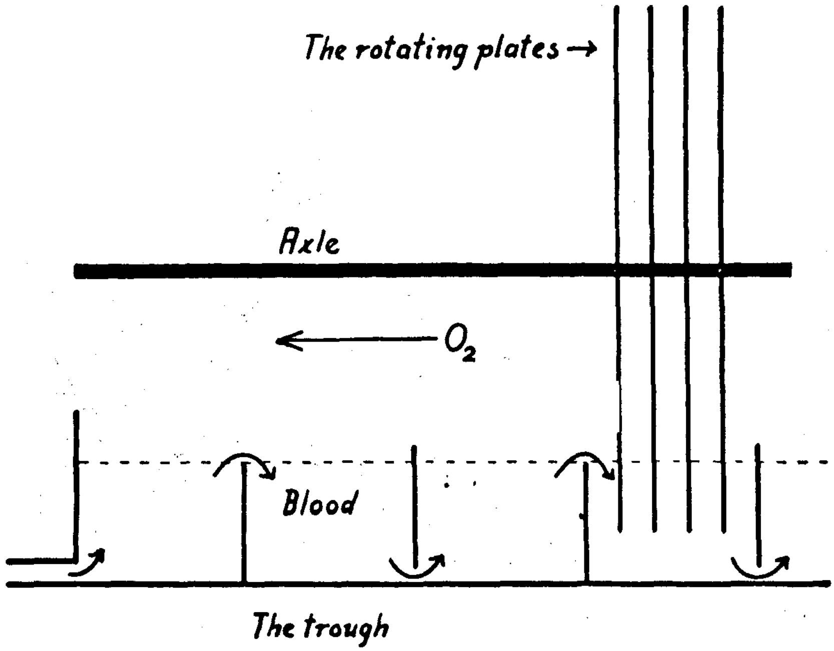

FIG. 28. A. Line drawing of pattern of Bjork oxygenator. (Bjork: *Acta Chir. Scandinav.* 96: Suppl. 137, 1948.)

mm. between groups of four (Fig. 28A, B). The rotating discs dip into a river of the blood to be oxygenated, and mixing in the river of blood is assured by a series of baffles which match the 8 mm. spaces between discs. The plates rotate at 120 rpm. and the blood content of the oxygenator is stated to be 250 cc. The plates dip into the blood to a depth of 15 mm., providing an area of blood film of 0.37 sq. meters exposed at any moment to the oxygen atmosphere. The minute film area is 44 sq. meters and the mean

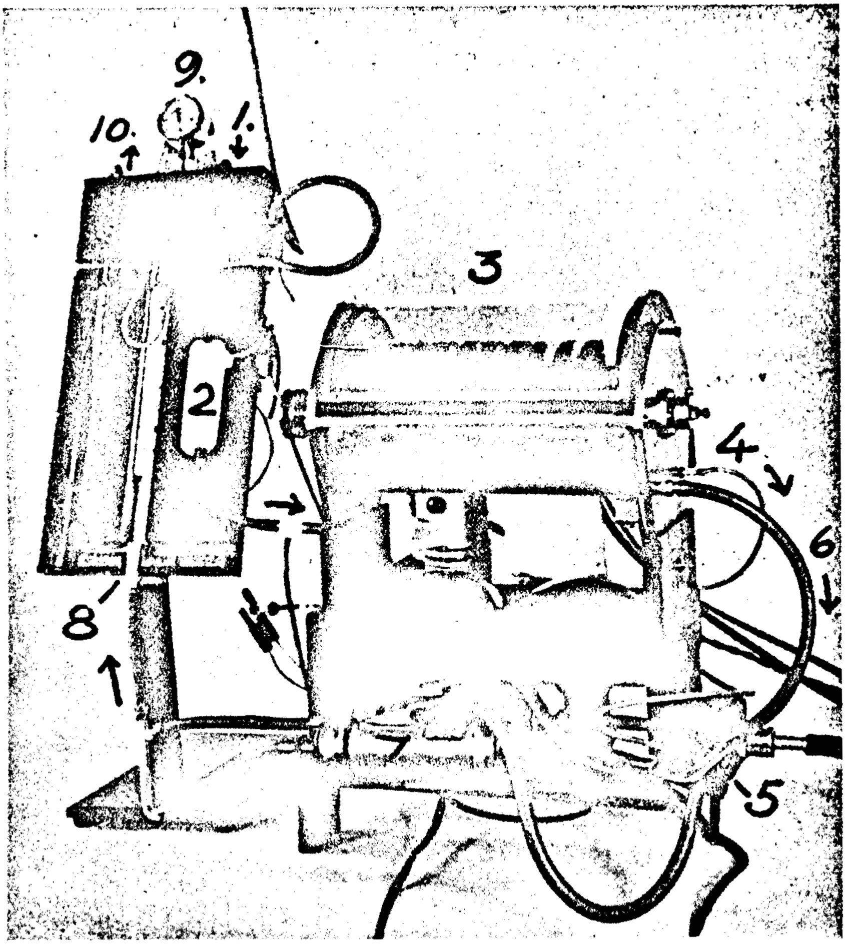

FIG. 28. B. The assembled pump-oxygenator of Bjork (from *Acta Chir. Scandinav.* 96:Suppl. 137, 1948).

film exposure time was said to be 0.39 seconds. Baffles consisting of 300 × 300 nickel screen were placed at the ends of the oxygenator chamber, but there was no bubble trap.

This oxygenator was capable of introducing a maximum of 110 cc. of oxygen per minute into the blood at 1071 cc. per minute of blood flow, but it could not saturate blood at flows above 300 cc. per minute. The average oxygen uptake was 48 cc. of oxygen per minute at an average blood flow of 680 cc. Unfortunately, the per cent oxygenation of the arterialized blood at these flows is not given in Bjork's paper. The plasma hemoglobin level increased in recirculation an average of 168 mgm.% in three hours. In brain perfusions of dogs, the hemolysis was variable, but the mean rise was 152 mgm.% in two hours. The white blood cell count decreased an average of 30% in two hours with a relative increase in lymphocytes.

The limited oxygenating capacity of this apparatus led to a modification which was designated by Bjork as the "large" oxygenator. It consisted of 50 discs, had a blood content stated to be 400 cc. and a minute area of blood film exposed to oxygen of 77 sq. meters. This "large" oxygenator introduced a maximum of 131 cc. of oxygen per minute into the blood at a flow rate of 800 cc. per minute. The average oxygen uptake with this apparatus was 90 cc. of oxygen per minute at an average flow rate of 762 cc. per minute. Again, the per cent saturation of the arterialized blood is not given, although it was considered by Bjork to be adequate.

THE CROSS-KAY MODIFICATION OF THE BJORK OXYGENATOR

The modification of this oxygenator which is used by Cross and Kay[2] is constructed of 59 Teflon-coated stainless steel (or entirely Teflon) discs, 0.4 mm. thick and 12.2 cm. in diameter. These discs are mounted 5 mm. apart on a horizontal shaft and enclosed in a cylinder of silicone-coated pyrex glass (Fig. 29). Fourteen hundred cc. of blood is introduced, and the discs dip into the blood pool to a depth of 4.1 cm. With this arangement, 0.84 sq. meters of disc area is exposed to oxygen at any one time. With 120 rpm., 110 sq. meters of blood film is exposed to oxygen per minute. The oxygen flow is five liters per minute through the apparatus and oxygen is warmed before introduction. No bubble trap or filter is used.

This oxygenator is capable of introducing a maximum of 207 cc. of oxygen per minute into the blood. During actual perfusion at 2000 cc. per minute blood flow and an arterio-venous oxygen difference of 6.8 volumes %, the apparatus introduced 136 cc. of

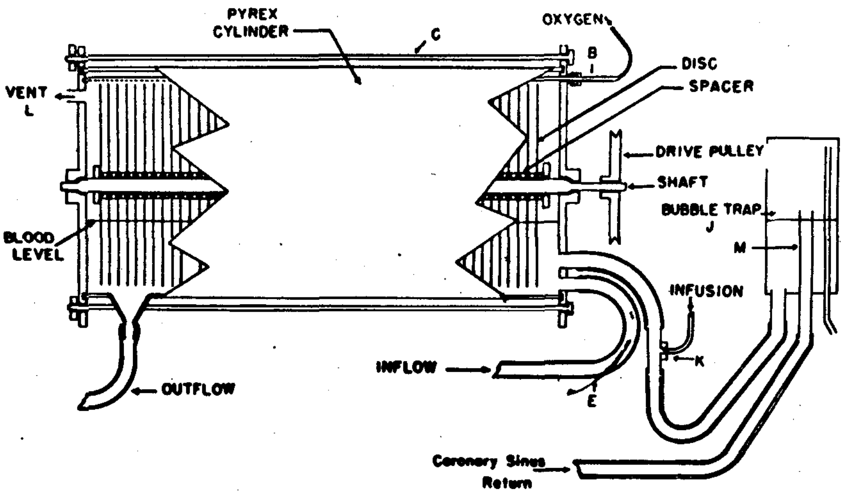

FIG. 29. Diagram of the Kay-Cross version of the Bjork oxygenator. (From *Proc. Soc. Exper. Biol. & Med.* 93:210, 1956.)

oxygen per minute into the blood while the arterial oxygen content was 18.6 volumes %. Hemolysis is from 10 to 160 mgm.% in 30 minutes.

OUR MODEL OF THE BJORK OXYGENATOR

In our laboratory, a Bjork oxygenator was constructed corresponding as precisely as possible to the description which he provides, except that the volume of blood was not as precisely held to a minimum as Bjork succeeded in doing. Our experience with the Bjork oxygenator indicated to us that foaming was frequently a problem, that hemolysis was occasionally excessive, and that oxygenation was not as effective as we had hoped, probably because of the larger volume in our model of the apparatus. Our model held 730 cc. of blood as compared to Bjork's 460 cc., and introduced 36.6 cc. of oxygen per minute at a flow rate of 500 cc.

OUR OXYGENATOR

The first vertical rotating disc oxygenator which was developed in our laboratory was designed to increase the area of film by use of much larger discs and a blood jet to film those discs placed so as to play blood near the center. It consisted of rotating stain-

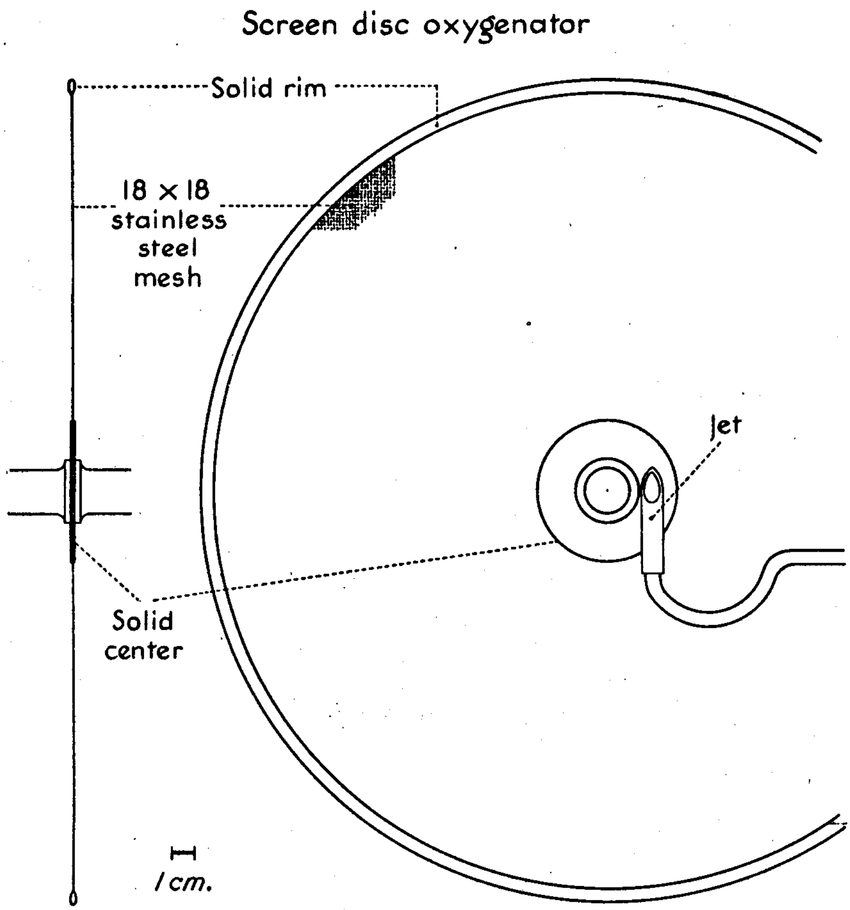

FIG. 30. Artist's drawing of the screen disc. (From *Ann. Surg. 134*:709, 1951.)

less steel discs mounted on a horizontal shaft. The discs were of several sizes up to 38 cm. in diameter. The venous blood formed a film over the discs, and centrifugal force and gravity caused the blood in the film to progress toward the periphery of the disc; it then dropped a few millimeters from the inferior margin into a collecting reservoir (Fig. 30). Several of these discs were mounted on a horizontal shaft in an oxygen atmosphere. The oxygenating efficiency of this pattern was determined with varying types of discs, various sizes of discs and at varying rates of rotation.

It was determined that a stainless steel screen disc made of

18 × 18 mesh stainless steel, made of wire 0.009 inch in diameter, was more efficient in oxygenating blood in this manner than were smooth discs or discs made of screening of finer or coarser mesh or of other wire diameter. It was also shown that in order to get adequate oxygen uptake, a 38 cm. stainless steel screen disc was the minimum acceptable. The oxygenating capacity of a single such disc rotating at 55 rpm. was 23 cc. of oxygen per 500 cc. of blood flow per minute. The volume of blood contained in the film on such a disc at any given moment at this blood flow was 60 cc.

Initial studies with this technique indicated a very high rate of hemolysis, which appeared at first to render the possibilities of the technique very limited. It became apparent, however, that a solid rim of carefully smoothed metal as a margin for the disc reduced the hemolysis produced by this portion of the apparatus to a very acceptable level.

The changes in various blood constituents other than the red blood cells were determined during 32 complete cardiopulmonary by-pass procedures with an apparatus utilizing a multiple disc oxygenator on this pattern.[6] These are shown in Table I. An oxygenator of this pattern having eight discs of 38 cm. diameter was utilized in the perfusion of our first two clinical patients in 1951.

TABLE I

ACUTE METABOLIC CHANGES IN THE SCREEN DISC OXYGENATOR. MEAN OF 32 TOTAL BODY PERFUSIONS IN DOGS

	Pre-Perfusion	*After 45 Minutes of Perfusion*
pH	7.33	7.38
pCO_2	35 mm. Hg	27 mm. Hg
CO_2 content	15.7 m.eq./l.	14.5 m.eq./l.
Blood buffer base	44 m.eq./l.	40 m.eq./l.
Serum Cl^-	108 m.eq./l.	117 m.eq./l.
PO_4^{---}	4.0 mg./100 cc.	4.2 mg./100 cc.
Pyruvic acid	1.7 mg./100 cc.	2.4 mg./100 cc.
Plasma Hgb.	40 mg./100 cc.	80 mg./100 cc.
Hematocrit	45%	40%
Hgb.	12.8 gm. %	12.2 gm. %
Total protein	5.5 gm. %*	4.8 gm. %
Albumin	2.3 gm. %	2.2 gm. %
WBC	$13,000/mm.^3$	$5,000/mm.^3$

3.5% CO_2 in oxygen surrounding discs.

* This value is low because of dilution by glucose solution left after rinsing out formaldehyde used for sterilizing during 1951 and 1952.

Neither patient survived, the first being lost because of our failure to be familiar with the anatomy of persistent atrio-ventricular canal and the second being lost because of a human failure in that the control circuit for the arterial pumps was not switched on by the operator at the beginning of the perfusion, and the pumps raced, exhausted the reservoir, and flooded the aorta with oxygen.

Continued studies indicated that a disc of larger diameter is more efficient. It was found that a single 50 cm. screen disc mounted as before introduces 36.5 cc. of oxygen per minute at a flow rate of 500 cc. per minute. The film volume per disc at this flow rate is 97 cc. The rate of rotation of the disc with the larger screen could be reduced to 20-24 rpm. without changing the film volume, oxygenating characteristics, or hemolysis.

The oxygenator which we presently use, therefore, is constructed of four 50 cm. stainless steel screen discs on a horizontal shaft which rotates at 23 rpm. (Fig. 31A, B). The pattern of the discs and the jets for provision of blood and oxygen are indicated in Figure 30. The four-disc unit is mounted in an enclosed chamber,

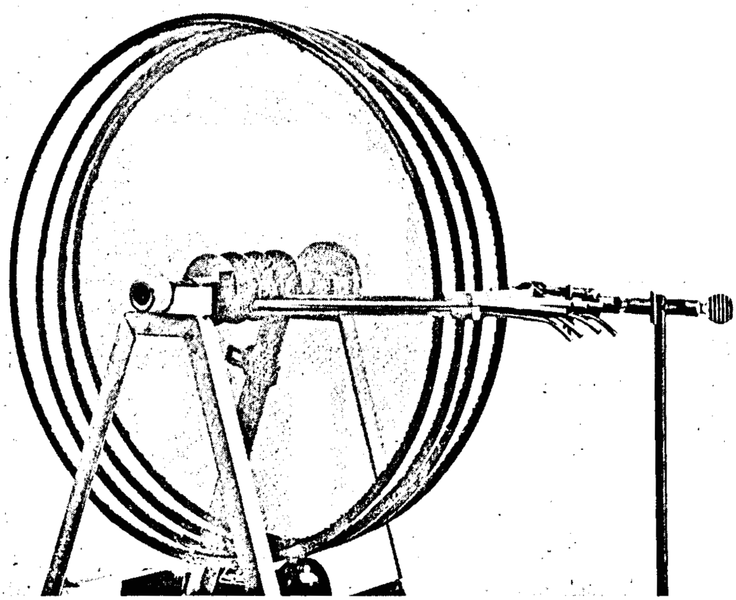

FIG. 31. A. Photo of mock-up of oxygenator, without the sheath and reservoir.

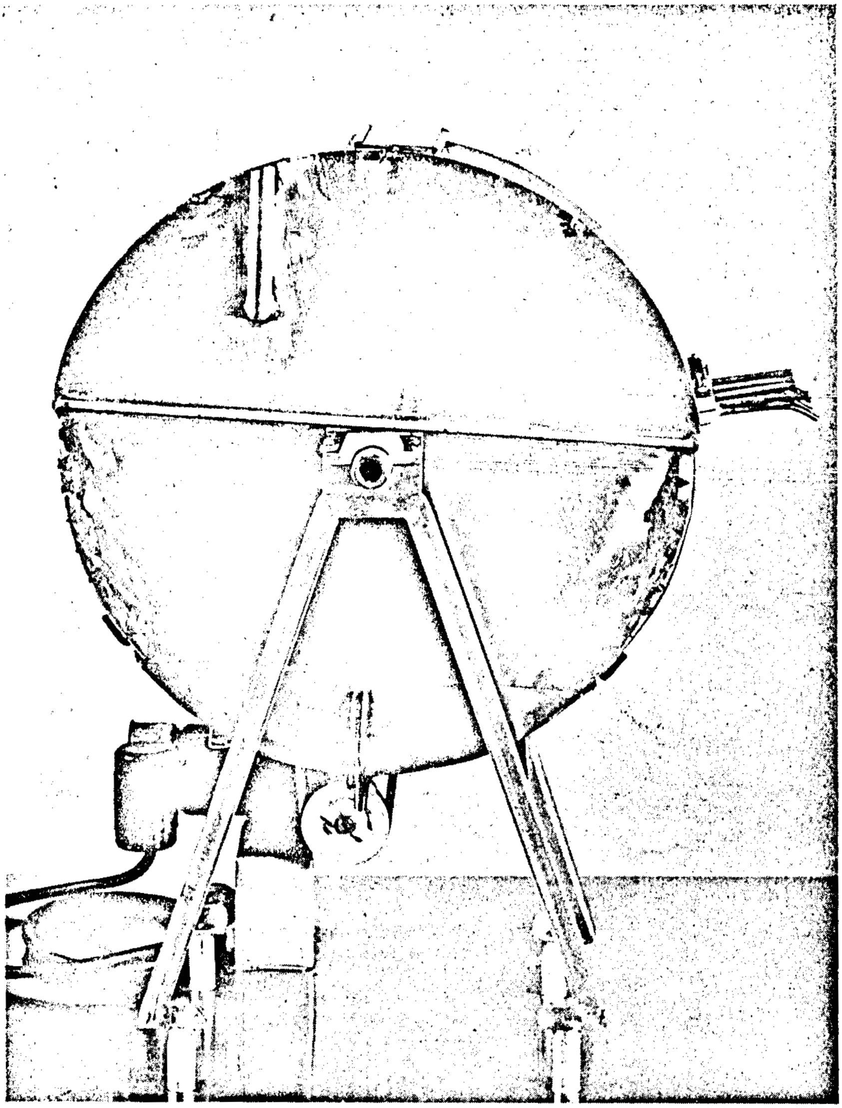

FIG. 31. B. The assembled oxygenator.

the bottom of which serves as a reservoir for the oxygenated blood as it drops from the discs. The blood volume of this apparatus, utilizing four discs with a flow rate of two liters per minute, is 988 cc., of which 600 cc. is in the reservoir and the remainder is in the film. Oxygen is run into the tank through four jets adjacent to the blood jets at a rate of 10 liters per minute. The average oxygen uptake at two liters per minute flow is 146 cc. per minute, Fig. 31A.

The hemolysis with this oxygenator is minimal, the average being less than 100 mg.% increase during an hour of perfusion. No filter as such is used, but a bubble trap has been designed in the laboratory, utilizing stainless steel sponge treated with silicone. This is a precautionary measure should the tank level inadvertently be carried too low, and it furthermore serves as a rather effective filter for particulate matter.

CRITERIA FOR EVALUATION OF OXYGENATORS

An objective measure for the quantitative evaluation of the efficiency of oxygenators appears to be valuable. We suggested in 1949 the definition of oxygenator efficiency as that volume of oxygen introduced per minute for each 100 cc. of blood required to prime the oxygenator.[4] This is an incomplete measure inasmuch as it does not take into account the increase in oxygen per cent saturation accomplished by one passage of blood through the oxygenator or the completeness of saturation of the "oxygenated" blood. If one specifies that the oxygenator should add a minimum of seven volumes % of oxygen to the blood and bring it to a point close to full saturation, then this definition of efficiency is useful. Comparison of various reported oxygenators on this basis is difficult because of the inadequacy of data provided in many publications.

Table II presents data relative to the performance of the 38 cm. screen oxygenator disc as compared with the 50 cm. screen oxygenator disc. The efficiency of these two discs is seen to be the

TABLE II

RELATIVE PERFORMANCE OF TWO SIZES OF SCREEN DISC OXYGENATOR AT FLOW RATE 500 ML./MIN.

	Efficiency of Disc	*Efficiency Whole Unit*	*Increase Oxygen % Saturation*	*Oxygen Added Per Minute Per Disc*	*Film Volume on Each Disc*	*Hemolysis mg. %/hr. in Dog Perf.*
38 cm.	37	14.4	4.6	23 cc.	60 cc.	<100
50 cm.	37	14.8	7.3	36.5 cc.	97 cc.	<100

TABLE III

PERFORMANCE FACTORS IN SEVERAL TYPES OF DISC OXYGENATOR

	Vol. Content (*cc.*)	*Oxygen Uptake* (*cc./min.*)	*Flow* (*cc./min.*)	*Plasma Hgb.* (*mgm. %*)	*Efficiency*†
Bjork					
"small"	250	48	680	96/2 hr.	19.2*
"large"	400	90	762		20.0*
Dennis	730	37	500	high	5
Cross and Kay	1400	136	2000	10–160/½ hr.	9.7
Dennis	988	146	2000	<100/1 hr.	14.8

* Not fully saturated.

† cc. oxygen added per minute per 100 cc. of blood in oxygenator.

same, but the smaller one provides an inadequate rise in oxygen saturation in a given passage whereas the larger is adequate. Hemolysis is minimal in both.

Table III presents information concerning Bjork's small and large oxygenators and our model of the Bjork apparatus, together with data concerning that of Cross and Kay and of the apparatus which we are presently utilizing. Use of this means of making comparison appears to us to favor that apparatus currently in use in our laboratory.

Other factors of importance in relation to evaluation of oxygenators are related to the ease of manufacture, the durability, the ease of cleaning, and the certainty of sterilization. The four-disc screen oxygenator can be taken apart, cleaned, assembled completely, and packaged for autoclaving by one person in a period of fifteen minutes.

Finally, the risk of total body perfusion which has impressed us most is that of air embolization. This is a risk which is apparently eliminated provided only that the reservoir level to which the blood drops is within a few millimeters of the bottom edge of the discs.

CONCLUSION

We are highly pleased with the performance of the rotating screen disc oxygenator described herein. It is efficient, easily cleaned and sterilized, and not productive of air embolism. It has been used regularly in over 1000 successful animal perfusions.

It has been utilized in a series of clinical cases, the first in 1951, and the earliest successful one in June, 1955.

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